

Prognostics and Condition Based Maintenance (CBM) A Scientific Crystal Ball

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Abstract - *Scientists at the Pacific Northwest National Laboratory (PNNL) have examined the necessity for understanding and controlling the aging process of both safety-specific plant components and the infrastructure that supports these processes. In this paper we examine the preliminary development of aging precursor metrics and their correlation with degradation rate and projected machine failure.*

Degradation specific correlations are currently being developed at PNNL that will allow accurate physics-based diagnostic and prognostic determinations to be derived from a new view of condition based maintenance. This view, founded in root cause analysis, is focused on quantifying the primary stressor(s) responsible for degradation in the component of interest. The derivative relationship between the performance, degradation and the underlying stressor set is used to gain a first principles approach to prognostic determinations.

The assumptions used for the design basis of process equipment have always been as much art as science and for this reason have been misused or relegated into obscurity in all but the nuclear industry. The ability to successfully link degradation and expected equipment life to stressor intensity level is valuable in that it quantifies the degree of machine stress for a given production level. This allows two major improvements in the operations and maintenance (O&M) of process machinery: 1) the actual versus intended machine environment can be understood and brought into much better alignment, and 2) the end goal can define operations and maintenance strategies in terms of life cycle and economic management of plant assets.

A holistic infrastructure approach, as applied through a CBM framework, will allow intelligent, automated diagnostic and prognostic programs to provide O&M practitioners with an understanding of the condition of their machinery today and an assurance of its operational state tomorrow.

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I. INTRODUCTION

There is a growing need to develop and demonstrate technologies that can monitor and predict the remaining service life of key elements in our national civil infrastructure.¹ Operating experience from U.S. nuclear power plants indicates that degradation of power plant performance, as evidenced by unscheduled shutdowns, extensive maintenance, and reduced operational efficiency, occurs to a large extent because of vibration, bio-fouling, and erosion/corrosion mechanisms.² The goal of the Self-Diagnostic Monitoring System (SDMS) project is to provide a proof-of-concept demonstration of the effectiveness of a forward looking approach to diagnostic and prognostic technology for these mechanisms.

The Pacific Northwest National Laboratory (PNNL) Nuclear Energy Research Initiative (NERI) team selected specific reactor plant mechanical systems and components for investigation³ based on applicability to current and projected future reactor systems. The information gained through the Nuclear Regulatory Commission's Nuclear Plant Aging Research (NPAR) program⁴ was used for the selection of components and degradation mechanisms for the study. This part of the study concluded by recommending the investigation of pump-motor degradation and filtration operations that result in degraded states.

II. THE TIME FORWARD SCENARIO

The investigative tack taken by the PNNL team is termed a time forward scenario approach, in that it attempts to predict the behavior of components and structures based on the measurement of precursive stressors. This approach was derived from extending the evolutionary concept of condition based maintenance (CBM) to its logical conclusion.

Maintenance has evolved over the years from simply reacting to machinery breakdowns (1- corrective maintenance or CM - see Figure 1), to performing time-based preventive maintenance (2- PM), to today's emphasis on the ability to detect early forms of degradation in predictive maintenance (3- PdM) practices. The incentive for each incremental step has been a clear reduction in the cost of operating and maintaining (O&M) almost any process facility. As shown in Figure 1, there is still one more plateau for the O&M team that aspires to maximize the utilization of facility assets and attain true condition based equipment management. The condition based operations and maintenance (CBO&M) approach is characterized by understanding the stressor levels intended during the

machinery design process, measuring suitable parameters to quantify the existing stressor levels, and correcting operating environments to make these levels compatible with economic production versus equipment lifetimes. The measurement of machine stressors to predict degradation rates and remaining life gives rise to the term time forward scenario. Such an approach can provide the O&M team with the information necessary to select and follow the optimum asset management path.



Figure 1 Evolution of Condition Based Maintenance

Condition-based operations and maintenance (CBO&M) is aimed at the immediate detection and diagnosis of off-normal equipment operation and the identification of the root cause stressor(s) responsible for this condition. This final evolutionary step, illustrated in line 4 of Figure 1, is the real key to optimizing high value, critical, O&M processes.

Three things about CBO&M should be noted from the outset:

1. Operations have now been engaged and integrated into the maintenance equation by becoming responsible for recognizing and correcting the existence of an abnormal condition or stressor level.
2. Finding the root cause stressors (parameters outside the design envelope) responsible for the off-design condition is now the prime directive.
3. The maintenance task can be preplanned and streamlined to eliminate the brushfire urgency and huge parts inventories, and minimize the maintenance impact on production.

This approach yields a computerized real-time picture of the problem and a clear understanding of the solution, and can be computer generated and presented simultaneously to the operations,

maintenance, engineering, and administrations staff. Asset management can now proceed using informed decisions based on known conditions, defined degradation rates and, in most cases, accurate estimates of equipment remaining life (prognostics).

III. PRECURSIVE RELATIONSHIPS

The basic concept for CBM stressor-based analysis centers on the fact that by understanding the stressor characteristics, an anticipatory indicator is provided for mapping subsequent damage through the activation of a resulting degradation mechanism. Degradation mechanisms, the resulting physical damage, and the associated decrease in asset performance start with the application of a stressor to the component. In truth, stressors are a necessary part of a process component life. The design engineer sets the desired stressor intensity level so the degradation in the physical state of the component happens slowly enough for the equipment to last for a specified design life. In general, when the design limit of a stressor is exceeded, the component life expectancy starts to shorten to less than the projected design duration. Conversely, careful control of operational parameters can result in the opposite effect – extending the component life beyond that normally expected for the design failure point.

The most common procedure used to deal with degradation involves trending an index or parameter that relates to the performance of the equipment. Figure 2 shows a performance index that starts to decline from its normal operating band (NOB), reaches an alert level, and is subsequently analyzed to try and understand a reasonable projection for residual life. Failure is defined as the point at which the equipment no longer is capable of supporting the function for which it was designed. Associated with this method is a large cone of uncertainty that is created by extending the maximum and minimum slope of the trend until it reaches the predetermined failure level.

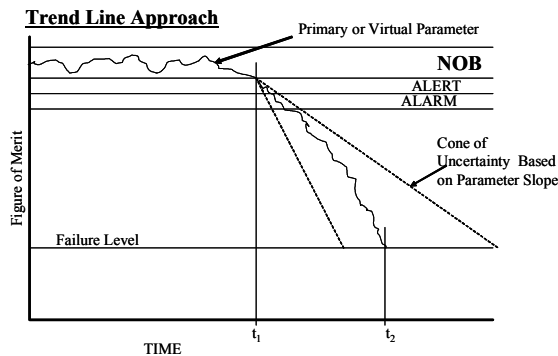


Figure 2 Time Line Approach to Failure Prediction

The premise of this methodology is that, by not trending a performance metric per se, but by focusing on trending the stressor characteristics, a precursive relationship can be derived that will allow a much more accurate projection of the remaining useful life. Figure 3 shows the expected result in narrowing the uncertainty by keying on the stressor itself.

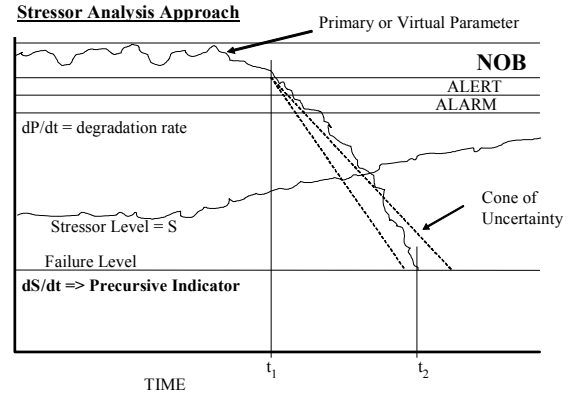


Figure 3 Stressor Measurement Effect on Prediction Uncertainty

The basis for such an expectation is as follows: The slope of the trended parameter gives a measure of the degradation rate of the performance. This is assumed to be a function of the rate of decline in the physical characteristics of the equipment as well. Experience from PM measurements has shown this assumption to be true if one accounts for the nonlinearity between physical attributes and their effects on performance. So we have:

$$\begin{aligned} dP/dt &= \text{perf degradation rate} \\ &\Rightarrow \text{physical degradation rate} \end{aligned} \quad (1)$$

Because the stressor intensity is responsible for the rate of physical and hence performance degradation, it follows that

$$dP/dt = DR(P) = F^P(S) \quad (2)$$

where S = stressor intensity.

In other words, the instantaneous degradation rate can be correlated to the stressor intensity by a functional relationship. Now taking this one step further,

$$dDR/dt = d^2P/dt^2 = dS/dt \text{ stressor trend or slope} \quad (3)$$

So by following the slope of the stressor intensity, we have a precursive measure of the rate of change in the performance degradation. Thus the stressor slope can be used to predict and to refine the path of the performance vector.

The rate of change in the slope of the stressor gives yet another precursive dimension for narrowing the uncertainty of the predicted performance path. This stressor gradient is the most sensitive, or root precursive indicator, for a time-linked correlation from stressors through to failure.

$$d^2S/dt^2 \Rightarrow \text{Root Precursor} \quad (4)$$

If a measure of this root indicator can be accurately determined, each level in the derivative chain can be integrated to provide an accurate physical description of the future condition and performance of the component. It also follows that as diagnosticians, our quest is a complete mathematical description of the stressor's derivative chain – its level, slope and gradient.

IV. STRESSOR FOCUSED DATA

The above mathematical development provides the foundation for a stressor to failure mechanistic correlation. The remainder of this paper presents the methodology developed to produce a proof of principal prognostic experiment for quantitatively developing such a correlation.

The two most predominant mechanisms that result in centrifugal pump failure are cavitation and vibration. The instrumentation required to quantify

stressor intensity and examine the physical effects of degradation are outlined below for the vibration class of failure mechanisms. Figure 4 will be used for reference in these discussions.

IV.A. Rotational Stressor Instrumentation

The class of rotational stressors results from an imbalanced condition in one of the rotating elements, or from misalignment of the shafts of the rotating components. This stressor set must also be inclusive of “other” multiple causes,^{7,8} and problems like “soft foot” mounting will be considered for intentional initiation and subsequent analysis.

Standard vibrational instruments were placed on both the pump and motor to provide a common reference for vibration diagnosis of machine faults. This instrument set consists of inexpensive displacement vibration sensors and a high sensitivity triaxial accelerometer for each component. The peak-to-peak vibration and acceleration data will be used to compare the sensitivity of the experimental instrumentation in detecting the magnitude of misalignment phenomena using these commonly installed instruments.

The **pump-motor misalignment instrumentation** system is designed to provide carefully quantified angular and parallel offset and to measure

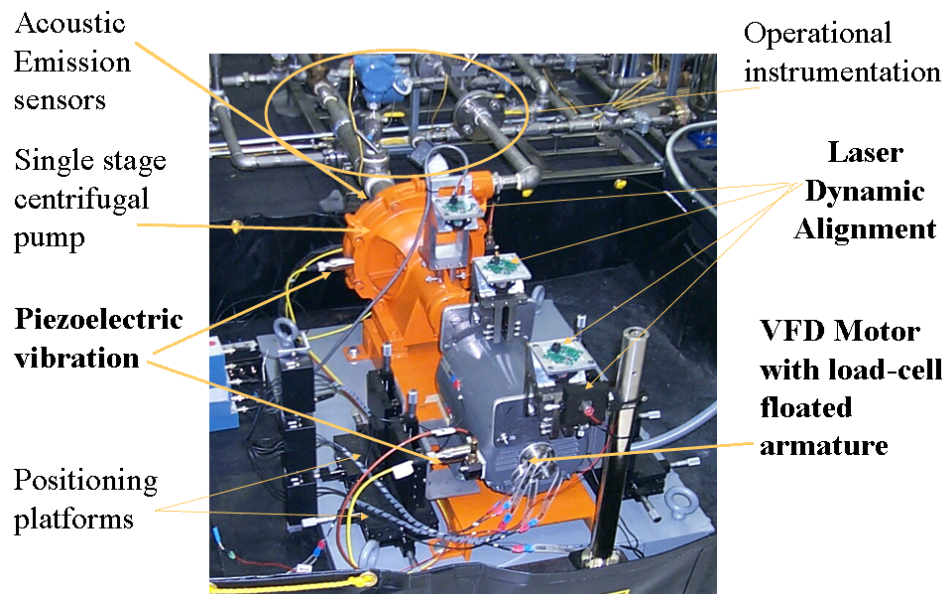


Figure 4. Stressor Instrumentation

the resulting static and dynamic bearing loading during operation of the pump-motor set. The ultimate goal is to allow a first principles approach to a prognostic algorithm that will accurately predict the reduction of bearing residual life as a result of misalignment of the driver from its driven component. Current predictive maintenance techniques do not provide sufficient accuracy to effectively detect or directly correlate misalignment data with residual life. The data from this experiment will also allow an investigation of dynamic laser alignment techniques for possible differentiation between misalignment and rotating balance conditions.

The motor base was removed and replaced with four independent tri-axial positioning platforms. This arrangement will allow fine adjustments (± 0.025 mm) in axial offset or angular skew in either static or dynamic modes. A dynamic laser alignment device was developed and fabricated at PNNL to provide a continuous indication of axial and angular alignment between the pump and motor. This device is accurate to ± 5 microns and provides a dynamic motion trace as well as the associated FFT. This instrument, coupled with the precise vernier control of the positioning platforms, gives alignment control for the experiment.

The **load cell system** characterizes the effects of static and dynamic rotational stressors. This requires a means of measuring the dynamic bearing loading in real time. The concept used here is to “float” the motor armature on a system of load cells. The load cells used are unique in that they are commercially available polymer-based units with a 10 K frequency response time. The sensor is an ultra-thin (0.012-mm) flexible printed circuit. The total measurement device is 14-mm wide and 203-mm long. The active sensing area is a 0.95-mm diameter circle at the end of the sensor. The sensors are constructed of two layers of polyester substrate. On each layer, a conductive material (silver) is applied, followed by a layer of pressure-sensitive ink. Adhesive is then used to laminate the two layers of substrate together to form the sensor.

Load cell mounting in the motor is crucial and unique to this application. The armature is “floated” on a complete radial and axial load cell set (nine total), as shown in Figure 5.

To avoid attenuation of induced vibration, as with epoxy attachment methods, the mounting of the load cells in the motor housing uses no adhesives. This unique mounting was achieved by milling out the bearing housing by approximately 5 mm, fabricating a 1-mm outer shim with integral 1.2-mm-thick “load pads” to focus the forces on the load cell

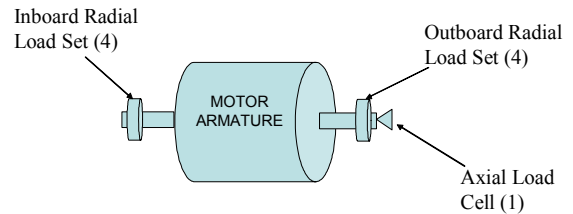


Figure 5 Floating Armature Concept

sensitive areas, placing the 1.2-mm-thick active load cells on each pad, then fabricating a 1-mm adjustment shim to create a very light interference fit. An iterative fitting process was necessary to produce the desired 40 to 55 Kg preload required to hold the bearing in place while not damaging the load cells during installation. During testing, this preload will be electronically removed. The four quadrant arrangement is shown in Figure 6.



Figure 6 Outboard Load Cell Penetration Arrangement

The load cells were individually exercised and calibrated per the manufacturer’s specifications prior to insertion in the motor. A precision hydraulic press was used to take each cell to 110% of its rated load (per manufacturer’s instruction) and a four point calibration curve was then generated for 0 to 100% of range for each cell.

IV.B. Data Acquisition

The polymer-based load sensor behaves as a variable resistance with a magnitude that varies proportionally with applied force. In the absence of load, the resistance of the sensor is very high, decreasing as load is applied. Measurement of applied load is most effectively achieved by biasing the sensor with a constant voltage and inputting the resulting load-dependent current into a simple negative feedback amplifier, thus converting it to a measurable voltage. This approach is described and recommended by the vendor.

Nine self-powered amplifiers were constructed to convert loads applied to the sensors to measurable voltages. The outputs of the amplifiers were supplied to two personal computer-based high-speed multi-channel acquisition cards. Commercial software provided the initial automated data acquisition and display of the sensor signals by periodically querying the cards for measured voltages at a user-defined sample rate. Sample rates could be adjusted up to approximately 10 K Hz. Data acquired during each sample period could either be displayed in a continuous fashion or archived to computer disk for subsequent analysis.

The combination of static and dynamic forces that are generated by intentionally induced rotational imbalance or misalignment between the pump and motor can now be used to correlate the quantitative degree of the induced stress to a corresponding integrated force-time effect on bearing life.

IV. C. Rotational Stressor Testing

Including baseline testing, six sequences of alignment and rotational imbalance were conducted. In reviewing the data, it must be remembered that the design of the test rig provides an inherent “soft foot” condition in that the motor base is basically a cantilevered angle bracket attached to a somewhat flexible positioning platform. The vibrational data set was recorded from: operational instruments, dynamic laser alignment (DLA), piezoelectric accelerometers, and dynamic load cell instrumentation. The DLA device was developed at the laboratory to show the physical motion patterns of the pump-motor under various degrees of misalignment. The data scenarios consisted of:

1. Aligned baseline test using best shaft-to-shaft alignment setting.
2. “Best Tune” data obtained by having the alignment technician “tune” the pump and motor alignment by dynamically centering and reducing the displacement oscillation pattern as viewed on the DLA computer display.
3. Resonance testing was accomplished by using the variable frequency drive (VFD) to increment the motor rotational speed from 10 Hz to the full 60 Hz. The frequency that displayed maximum deflection (resonance) was then determined.
4. Angular misalignment was introduced by moving the motor in 12 μ (5 mil) increments until a clear increase in load was observed on both the vibration and load cell instrumentation. Positional verification was achieved by shaft-to-shaft commercial laser techniques.

5. Parallel or axial misalignment was similarly introduced and verified using hand laser measurements.
6. Rotational imbalance was achieved by strapping a hose clamp with sequentially higher weight to the outer diameter of the motor coupling.

IV.D. Preliminary Results

Preliminary vibrational test results showed the following :

- Initial peak to peak displacement at 60 Hz operation (1750 rpm) was approximately 30 μ (12 mil).
- Using the DLA to “tune” the system, the observed vibration level was brought down by a factor of 2.
- FFTs at 1750 rpm calculated from DLA, vibration accelerometers, and dynamic load cell data showed similar peaks and broad band vibration from the soft foot condition (see Figure 7 a,b,c).

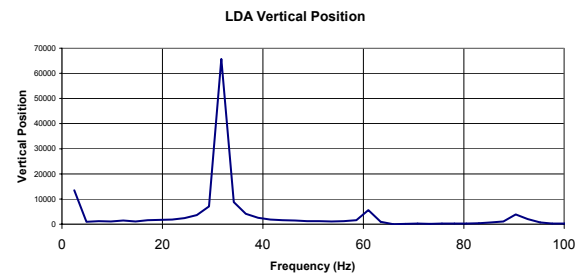


Figure 7a FFT of Motor Position Data

Figure 7b Motor Accelerometer Data

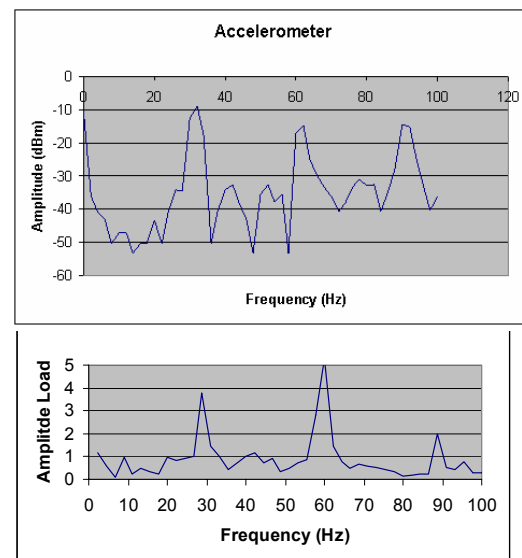


Figure 7c Motor Bearing Radial Load Cell

The figures show that these three separate perspectives, the laser position (DLA), standard accelerometer vibration data, and the dynamic bearing load cell data all exhibit the same basic characteristics. The soft foot condition of our test rig gives rise to a fairly broad floor of vibration frequencies, with three peaks that correspond to 1X, 2X, and 3X rotational speeds. While this result is well predicted in the literature,^{7,8} it is nonetheless satisfying to note that all three measurement systems are in agreement. What is of particular interest is that the forces actually sensed on the bearings were highest, not at the rotational frequency (~30 Hz), but at the 2X frequency. This suggests that harmonic vibration may play a stronger role in bearing fatigue than was previously thought. Mechanistic models are now being run to examine this possibility.

The above data was taken with an angular offset between the pump and motor. Figure 8 shows the FFT of the data taken during the same test by the axial load cell. As can be seen, the 1X rotational frequency is the only significant load being transmitted to the bearing in an axial direction despite the other gyrations being experienced by the motor.

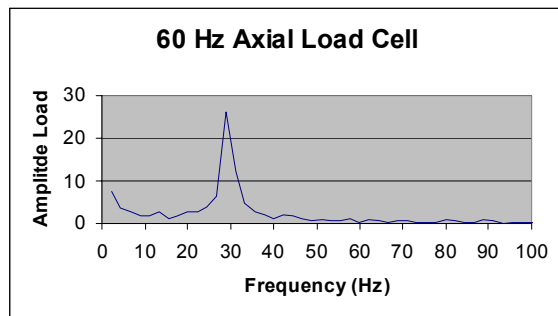


Figure 8 Axial Load Cell FFT at 60 Hz Operation

V. CONCLUSIONS

Scientists at the Pacific Northwest National Laboratory are performing a series of experiments that could dramatically impact the science of predictive machinery failure. These experiments are scheduled to continue through June 2002.

Preliminary vibration analyses show an excellent correspondence between the (laser) motor position indication, the vibration response, and the dynamic force loading on the bearings. Orbital and harmonic motion of the pump and motor are clearly indicated and can be readily correlated through the FFT of all three sensing systems. Driving a three-dimensional

visualization program with position data from the laser device allows an intuitive understanding of the primary oscillations and their associated harmonics.

Data produced by these experiments will be used to generate a new and definitive set of correlations linking degradation stressors to resulting degradation rates and failure prognostics. The correlations will be applicable to current as well as future generations of fossil and nuclear reactor power plants. The methodology points the way to real-time diagnostic/prognostic predictions that will pay significant dividends in terms of predictive accuracy, root cause resolution, equipment reliability, and resource management under normal and upset conditions.

VI. REFERENCES

1. L. J. BOND, "Predictive Engineering for Aging Infrastructure," *SPIE* 3588, 2-13 (1999).
2. D. B. JARRELL et al., *Nuclear Plant Service Water Aging Degradation Assessment*, NUREG/CR-5379, Volume I, PNL-6560 (June 1989), Volume II, PNL-7916 (October 1992).
3. D. B. JARRELL and L. J. BOND, "Equipment Operation Without Failures for Fourth Generation U.S. Reactors," *SPIE* 003/3 (2001).
4. M. SUBUDHI, *Nuclear Plant Aging Research (NPAR): Summary of Results and Their Uses*, TR-3270-1/95, Brookhaven National Laboratory, Brookhaven, New York (1995).
5. "Erosion by Cavitation or Impingement," ASTM special technical publication no. 408, Atlantic City symposium proceedings, (1966).
6. T. J. HOLROYD, *The Acoustic Emission & Ultrasonic Handbook*, Coxmoor Publishing Company, Oxford, England (2000).
7. R. C. EISENMANN and R. C. EISENMANN JR., *Machinery Malfunction Diagnosis and Correction*, Prentice-Hall, Inc., Saddle River, New Jersey (1998).
8. J. PIOTROWSKI, *Shaft Alignment Handbook*, Marcel Dekker, Inc. New York (1995).

